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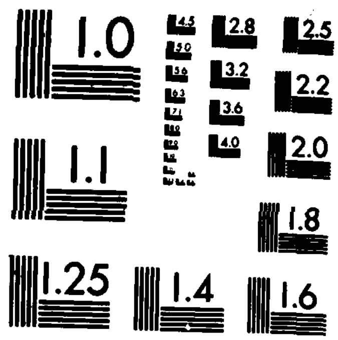
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FINAL REPORT

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ADVERSE PRESSURE GRADIENT CORNER FLOWS

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INTRODUCTION

This project was initiated in order to examine the nature of local flow separation along a streamwise corner in the presence of an adverse pressure gradient. Our results have shown that when the flow separates, a bubble is formed in the corner region which emanates from a singular point on the corner line. The presence of the bubble deflects the adjacent primary flow away from the corner to the extent that the local mean velocity vector is generally skewed in both pitch and yaw. These conditions correspond to a relatively hostile environment for a sensing probe, inasmuch as the mean flow is arbitrarily skewed, and moderate-to-high turbulence intensity fluctuations exist within the separation bubble and in the adjacent flow.

In order to quantify local flow behavior under these conditions, two complementary studies were pursued, namely: (1) the acquisition of mean flow data in a rectangular diffuser with locally detached flow present in the corner regions and (2) the development of a hot-wire response model to accommodate an arbitrarily skewed mean flow across the sensing element. One of these studies, namely the acquisition and analysis of mean flow data, was undertaken in order to gain insight into the nature of a corner separation bubble and its influence on the surrounding flow. The complementary hot-wire response study was pursued in order to develop a reliable method for measuring the mean velocity vector in both magnitude and direction and all six components of the Reynolds stress tensor in a low-to-moderate intensity, three-dimensional flow field. The current state of affairs with respect to progress made in each area is summarized below.

SUMMARY OF ACCOMPLISHMENTS

<u>Rectangular Diffuser Flow Study</u> Initial flow visualization data were taken in a variable-divergence-angle, rectangular diffuser composed of two symmetrically diverging walls and two parallel side walls, with an 8:1 inlet aspect ratio. The results indicate that local corner flow separation, when present, always occurs simultaneously in all four corners of the diffuser. For a moderately high inlet Reynolds number ($R_e = 10^5$) and modest total divergence angle ($2\phi = 8^o$), the flow detached locally in the near corner region almost immediately after the adverse pressure gradient was encountered to form a separation bubble in each corner. One of the distinctive features of this bubble is that limiting wall streamlines on adjacent walls bounding the corner are not symmetric about the corner line, but form, instead, an "S"-shaped pattern about this line. On the diverging wall, these streamlines terminate along a locus of points which can be interpreted as being a detachment line, while on the parallel wall these streamlines terminate along a line interpretable as a reattachment line. Flow on the outer surface of the bubble must be spiral-like in nature to accommodate this type of detachment-reattachment pattern. These observations are described in more detail in a thesis [1] and in a recent publication based on this study [2].

Another aspect of separated corner flow is that near-wall velocity profiles in the forward-facing flow portion of the bubble are not collateral. The mean flow also undergoes a severe turning angle (greater than 45 deg.) within the viscous sublayer. This behavior was determined by comparing limiting wall streamline behavior with flow angle measurements in the forward-facing flow portion of the bubble. These comparisons also indicated that flow outside the viscous sublayer was only moderately skewed, so that a

Preston tube could be used to measure the streamwise component of the local wall shear stress within the forward-facing flow portion of the bubble. When local wall shear stress values determined in this manner were used to normalize axial mean velocity profile data in this region, the results indicated that local law-of-the-wall behavior applies well into the bubble when the corner is approached either along the diverging wall or along the parallel end wall.

This result has important implications from a computational point of view, because it implies that the law-of-the-wall can be applied as a near-wall boundary condition (wall function) along the first mesh line parallel to each bounding wall of a corner, even in regions close to a zone of locally reversed flow. This near-wall boundary condition is commonly applied in predictions of wholly attached corner flows using codes based on two-equation (k-ε) closure models. The applicability of commonly applied wall functions for the turbulence kinetic energy (k) and the dissipation rate (ε) has not yet been investigated, primarily because local turbulence data within and near a corner separation bubble are not yet available. These data should ideally be taken with LDA-type instrumentation, which can accommodate locally reversed flow and high intensity turbulence fluctuations. Inasmuch as this type of instrumentation is not yet available within our department, an interim hot-wire technique was developed which can accommodate moderate intensity fluctuations and an arbitrarily skewed mean flow across the sensing element. Although this technique will not enable the separation bubble to be probed in great detail, the flow adjacent to this bubble can be probed with reasonable confidence, inasmuch as skewness angles and fluctuation levels in this region are relatively moderate. The distinguishing features of the technique we have

developed are described briefly in the next section.

Hot-Wire Response Model Study A hot-wire response model was formulated in order to facilitate Reynolds stress measurements in a mean flow which is arbitrarily skewed in both pitch and yaw. This type of flow exists not only within a rectangular diffuser in the near vicinity of a corner separation bubble, but also along wing-body junctions, within curved ducts, and within uncurved ducts with swirling inlet flow or with swirl induced by duct rotation. The hot-wire techique we have developed is thus applicable to a wide variety of three-dimensional flows where low-to-moderate tubulence itensity conditions prevail.

The present method is based on the sequential use of a single rotatable slant wire probe and a single normal wire probe in conjunction with a single-channel constant temperature anemometer. At each point in the flow, the slant wire probe is first rotated in 90-degree increments in order to determine the magnitude and direction of the local mean velocity vector from four mean-bridge voltage readings. The slant wire probe is then rotated to eight angular positions relative to the plane formed by the resultant mean velocity vector and the axial flow direction. When mean and mean-square fluctuating bridge voltage data taken in these eight positions are supplemented with normal wire data, all six components of the Reynolds stress tensor can be determined from a simplified system of linear response equations.

A unique feature of the present method is that the slant wire probe is located in eight planes which correspond to so-called "optimum planes," i.e., planes in which the wire is sensitive only to two mutually perpendicular

fluctuation components. These planes are, in general, non-orthogonal, and their relative orientations depend primarily on the skewness level of the flow. When normal and slant wire sensors are located in these planes, the response equations are uncoupled to the extent that a 3 x 3 linear system can be solved for three of the six Reynolds stress components, and the remaining components can be determined by solving a 2 x 2 system and an explicit algebraic equation. The details of this technique are described in a recently completed thesis [3]. The overall method has been presented on two occasions at national [4] and international [5] conferences concerned with measurement techniques in complex flows.

The relative merits of our technique have been examined by means of measurements in fully-developed turbulent pipe flow under simulated skewed flow conditions. The results have been presented and discussed previously [3-5], and show that the local mean velocity vector can be determined with good accuracy in a three-dimensional, low-to-moderate intensity flow, when the mean flow is arbitrarily skewed in pitch and yaw, and skewness levels are as great as 30 degrees. These results also indicate that all six components of the Reynolds stress tensor can be determined with a level of accuracy which exceeds that of competitive triple wire techniques.

FUTURE PLANS

Although the hot-wire technique we have developed has not yet been applied to measurements within our rectangular diffuser flow facility, it is contemplated that data will be taken as soon as additional funding becomes available. The local flow structure within and near a corner separation

bubble will also be probed with LDA instrumentation if an equipment grant proposal now pending is funded. We also plan to examine the full capabilities of our hot-wire response model by making measurements in the near field of a circular jet emanating from fully-developed pipe flow under simulated skewed flow conditions. In this manner we should be able to determine the limitations, if any, of our response model when applied to a three-dimensional flow where moderately high turbulence intensity conditions prevail. This work will also include a reformulation of the present response model to a model which applies for probes aligned normal to the axial mean flow. This model will complement the present model, which is based on measurements with probes aligned with the axial flow direction. Implementation of this work will be pursued subject to the availability of funds from governmental agencies for proposals now pending or to be submitted in the near future.

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